How to study the Early Universe: the ALICE experiment at CERN

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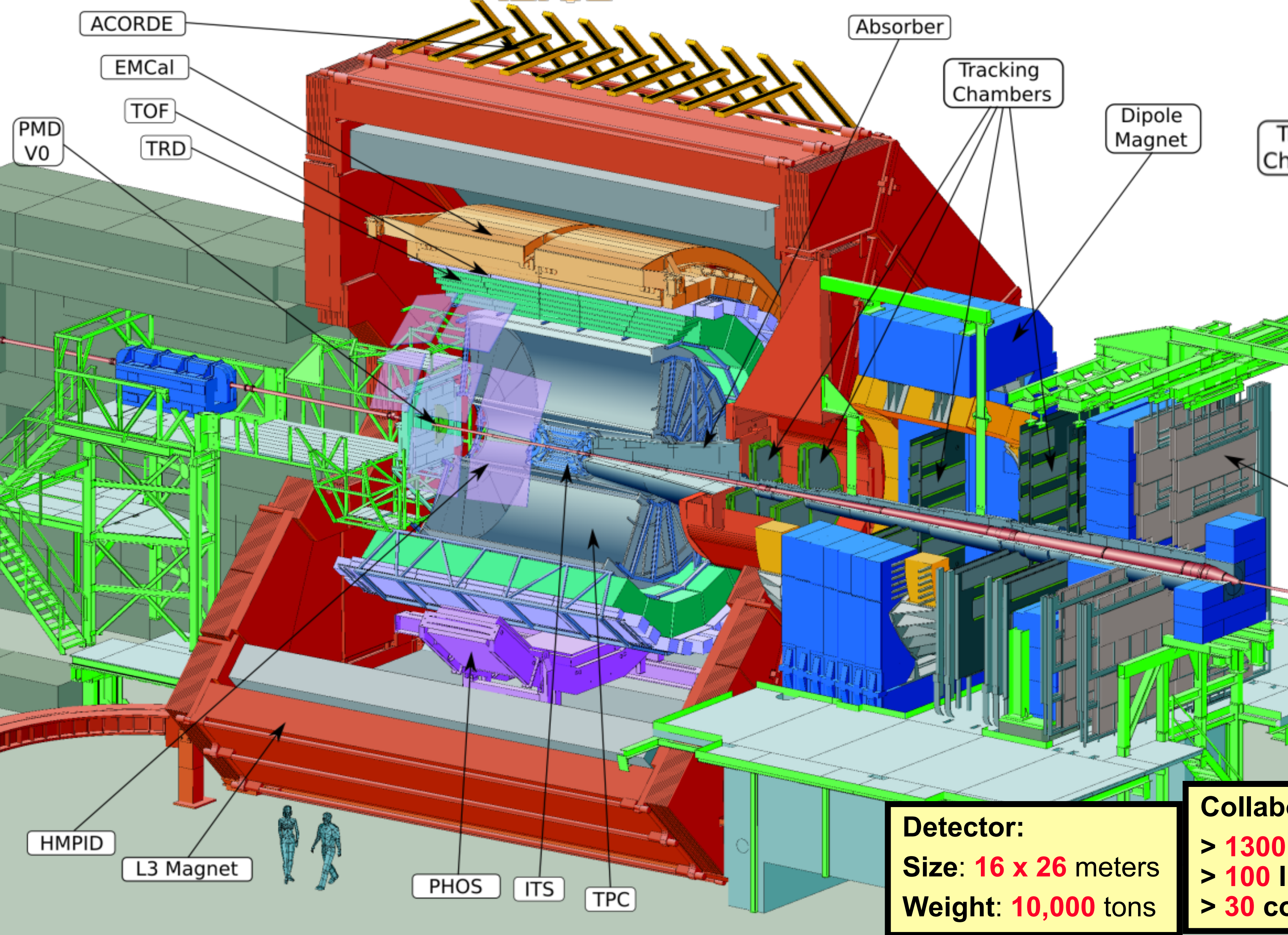
INFN Frascati

International Masterclass – LNF
February 10, 2014

A Large Ion Collider Experiment

European Organisation for Nuclear Research



Detector:

Size: 16 x 26 meters

Weight: 10,000 tons

Collaboration:

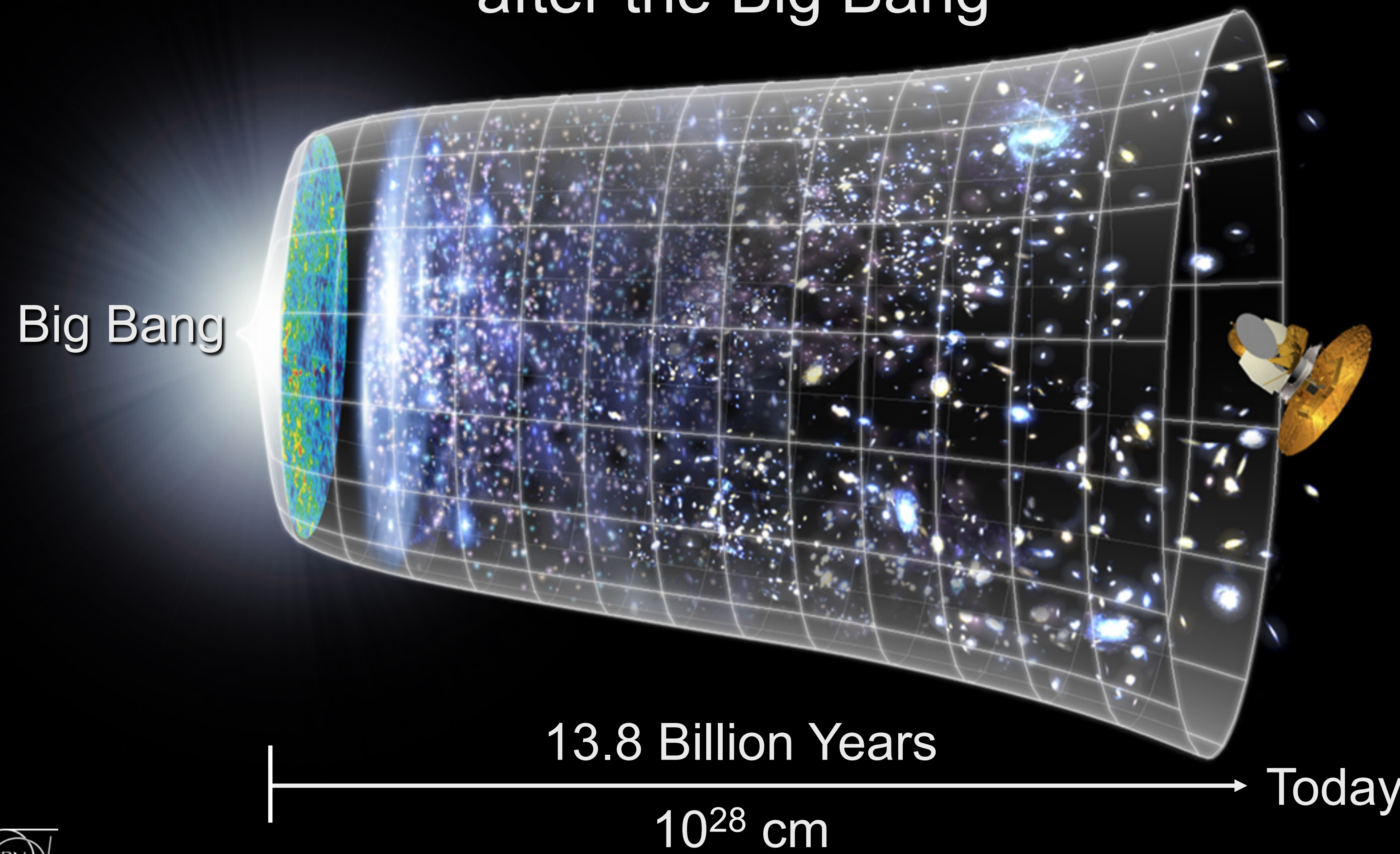
> 1300 Members

> 100 Institutes

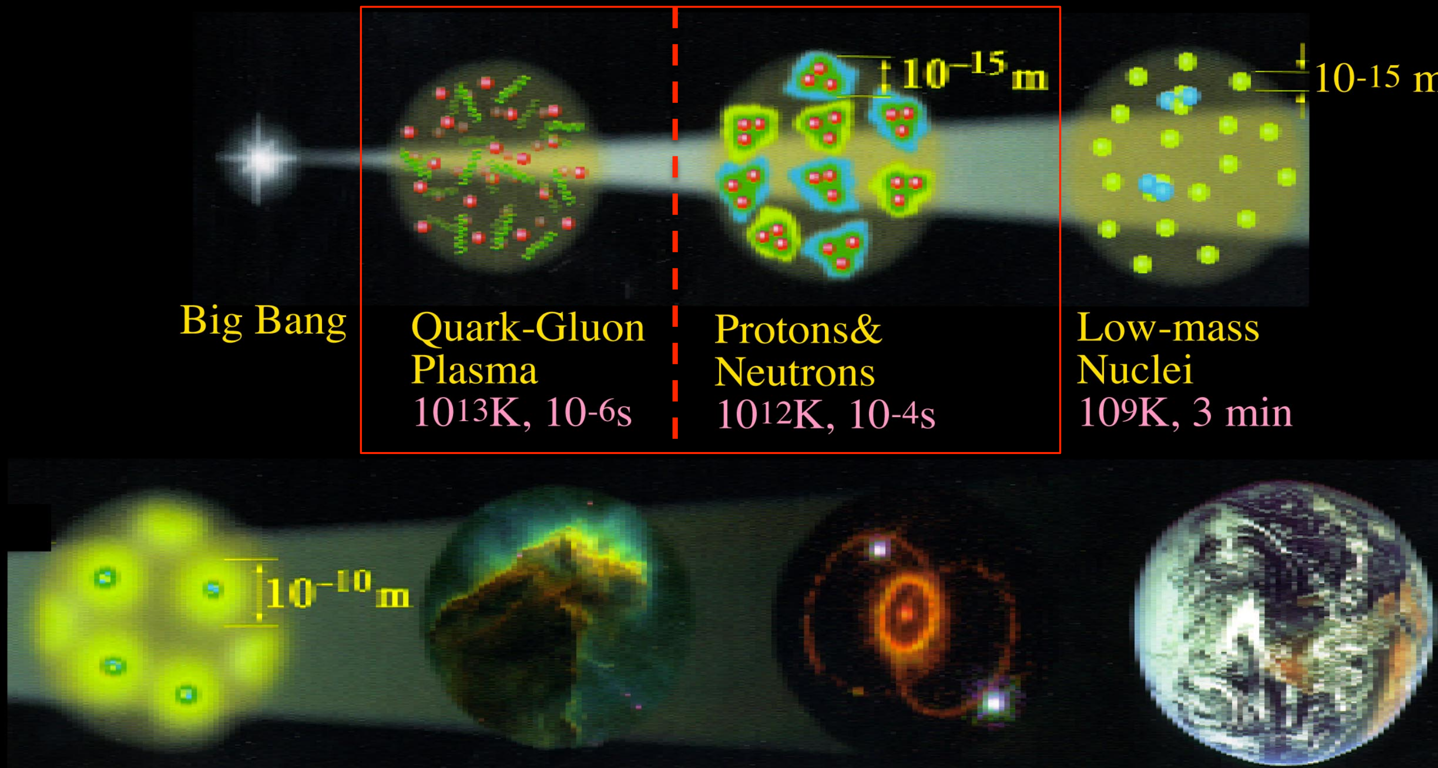
> 30 countries

An Important Scientific Challenge:

to understand the very first moments of our Universe after the Big Bang



History of the Universe



Big Bang

Quark-Gluon Plasma
10^{13}K, 10^{-6}s

Protons& Neutrons
10^{12}K, 10^{-4}s

Low-mass Nuclei
10^{9}K, 3 min

Neutral Atoms
4000K, 10^{5}y

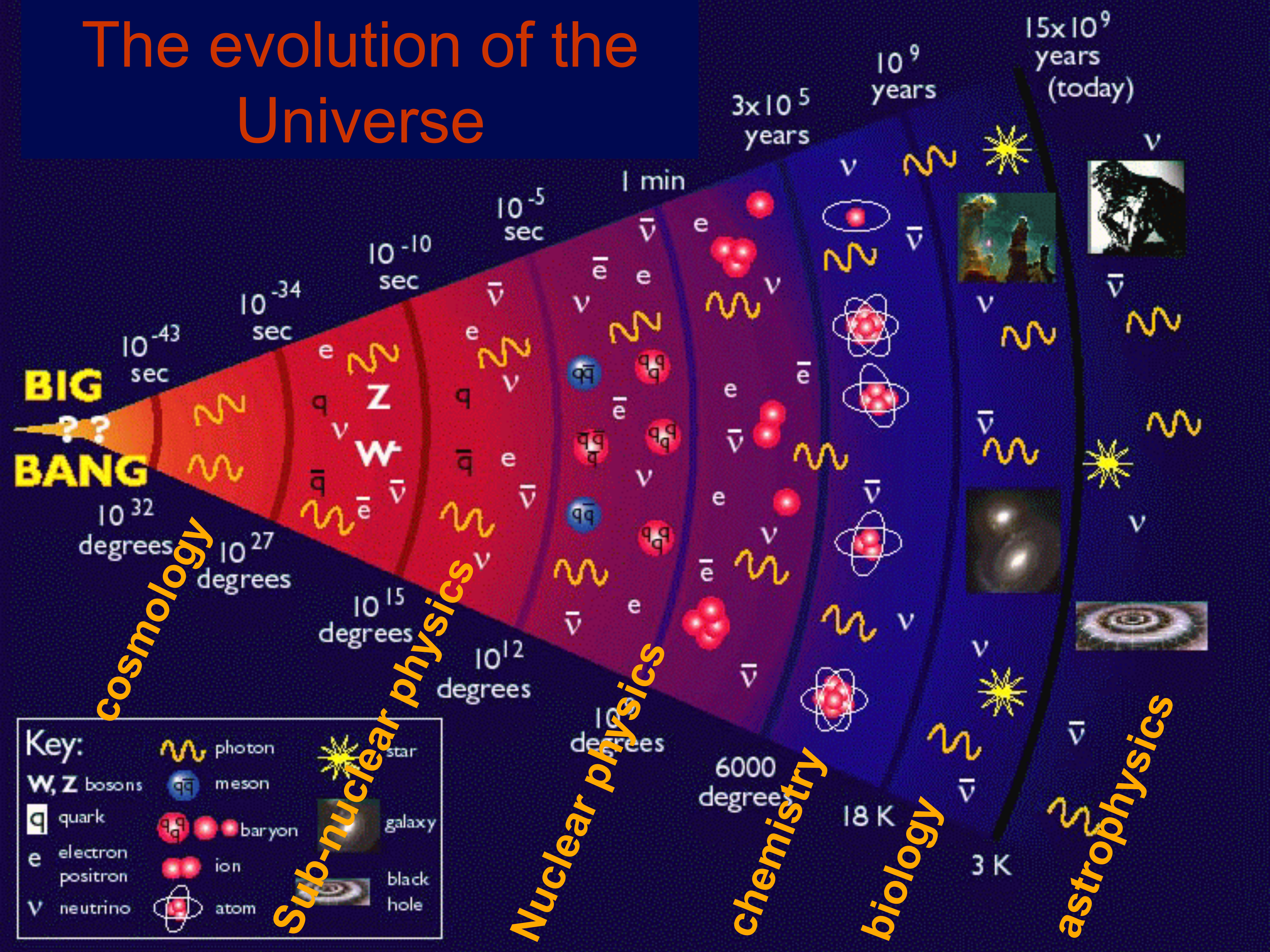
Star Formation
10^{9}y

Heavy Elements
$>10^{9}$y

Today

Source: Nuclear Science Wall Chart

The evolution of the Universe



In order to understand the deepest nature of the matter we have to:

-create the initial conditions of the Universe

-create and study all the possible particles (carriers of the information)

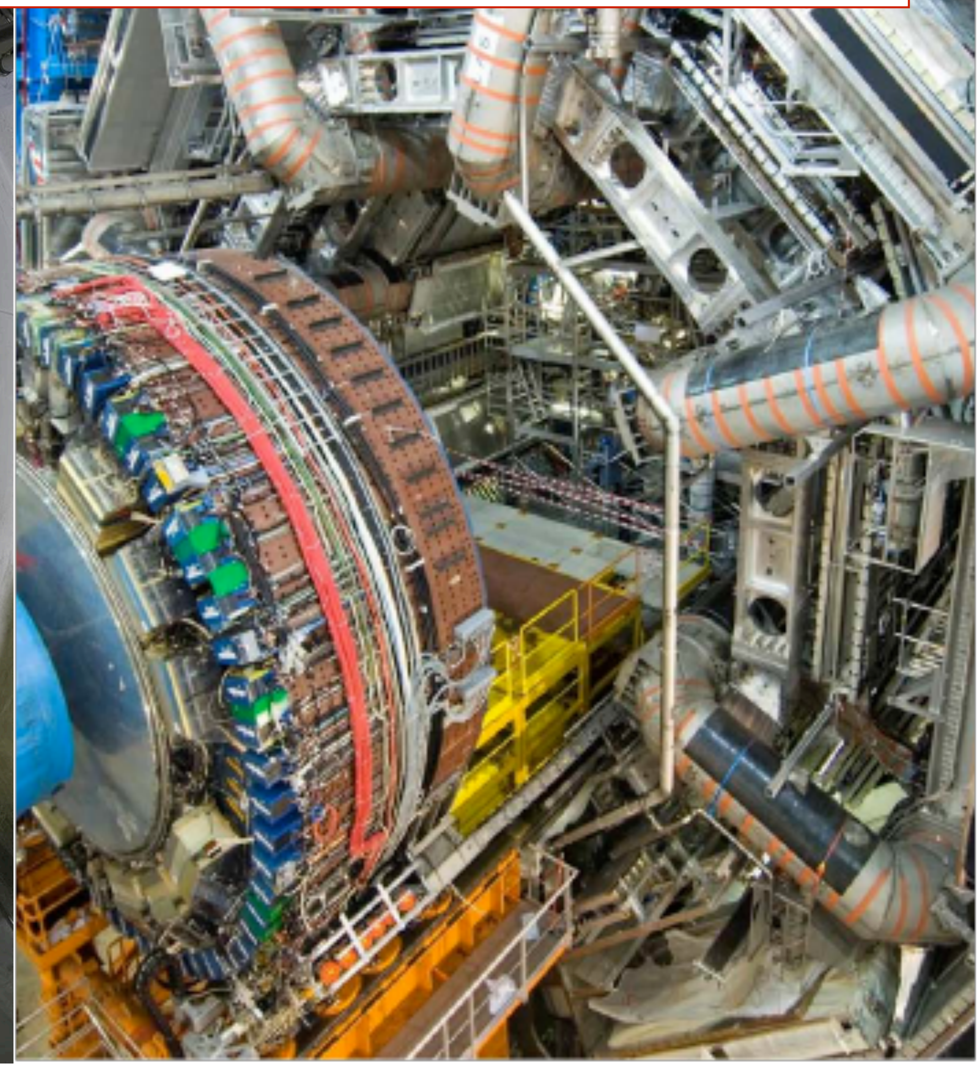
Particle Factories: the accelerators

Colliders

LHC at CERN, Geneve 2009

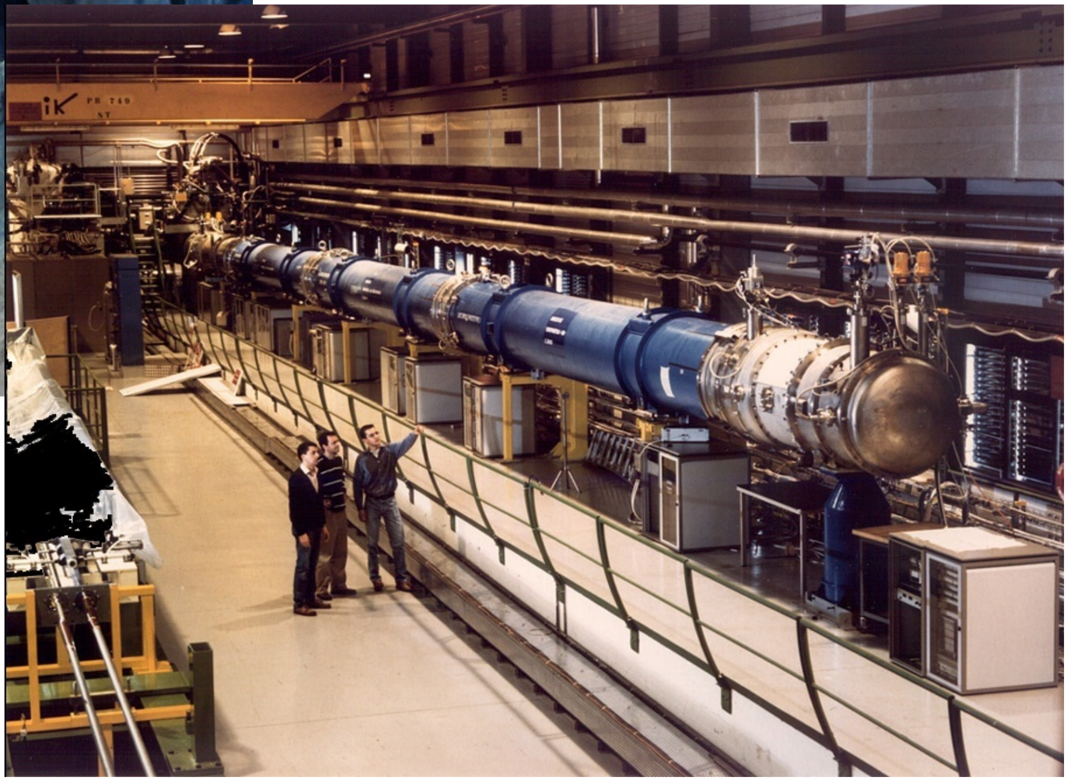
The global adventure

Everything started more than 20 years ago



LHC needed years of R&D

Construction of one of the cavern hosting the experiments



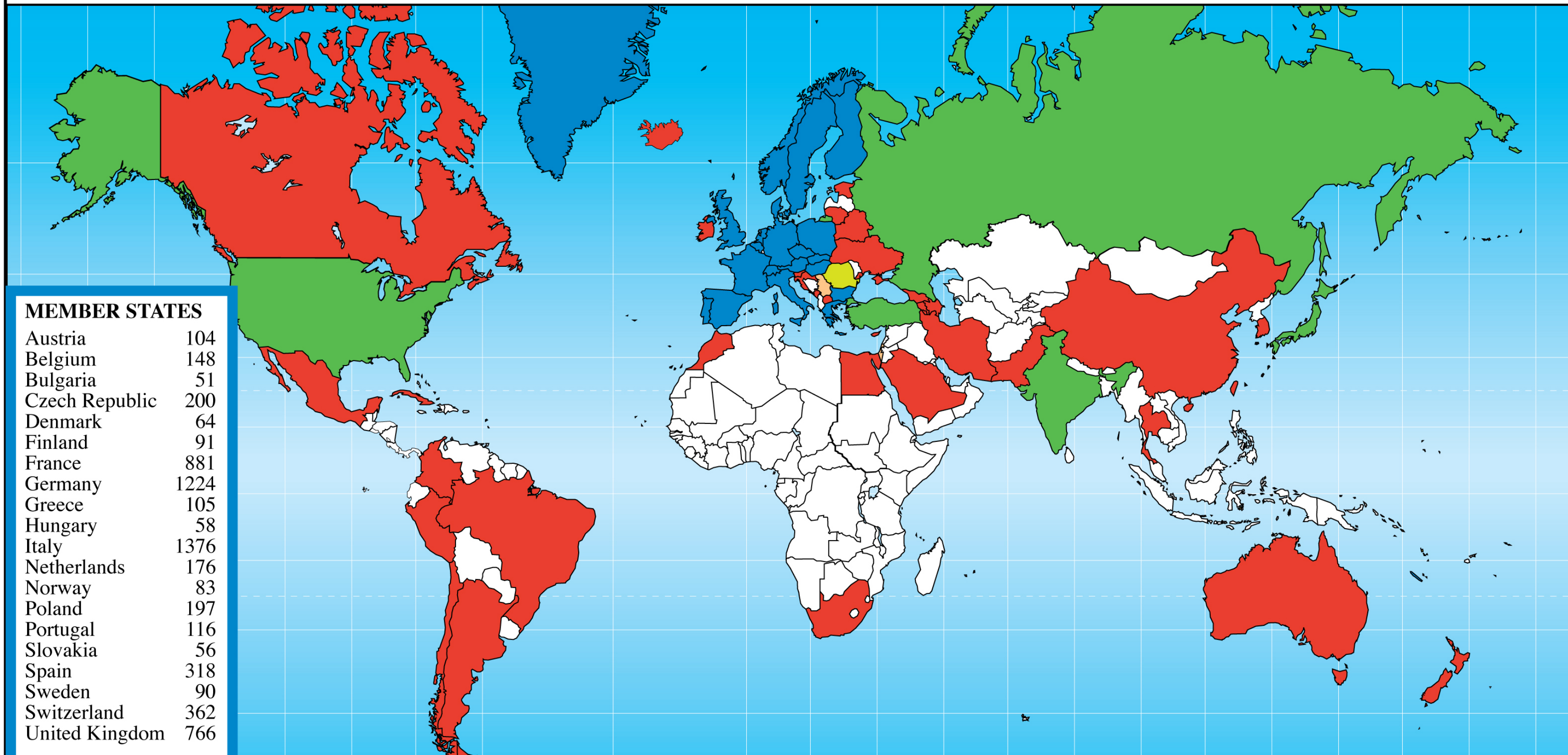
Dipole magnets string test


CAUTION
Helium Release Point
No stay zone
Point de rejet d'hélium
Stationnement interdit

Accelerator Control Room

Science is getting more and more global

Distribution of All CERN Users by Location of Institute on 2 September 2013



MEMBER STATES

Austria	104
Belgium	148
Bulgaria	51
Czech Republic	200
Denmark	64
Finland	91
France	881
Germany	1224
Greece	105
Hungary	58
Italy	1376
Netherlands	176
Norway	83
Poland	197
Portugal	116
Slovakia	56
Spain	318
Sweden	90
Switzerland	362
United Kingdom	766

6466

OBSERVERS

India	154
Japan	224
Russia	899
Turkey	106
USA	1787

3170

CANDIDATE FOR ACCESSION

Romania	82

ASSOCIATE MEMBER IN THE PRE-STAGE TO MEMBERSHIP

Israel	57
Serbia	30

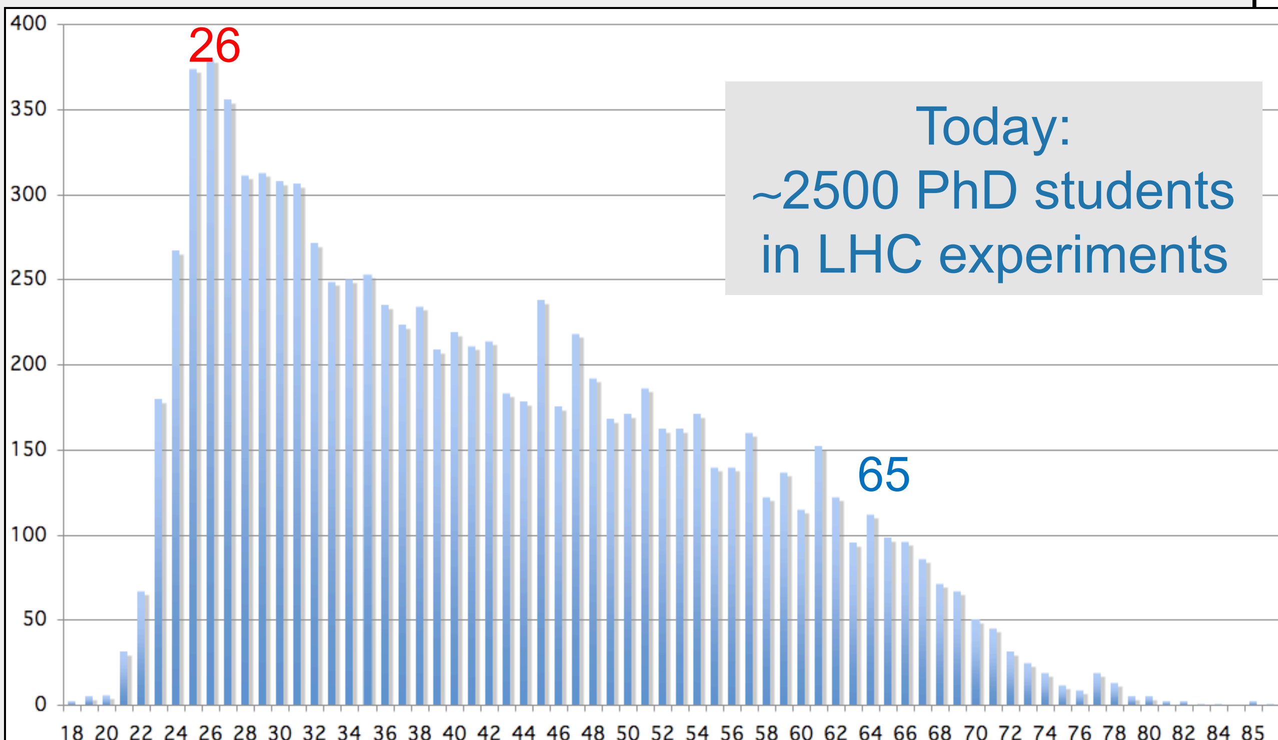
OTHERS

Argentina	17
Armenia	17
Australia	39
Azerbaijan	2
Belarus	23
Brazil	110
Canada	154
Chile	7
China	130
China (Taipei)	70
Colombia	11
Croatia	25
Cuba	3
Cyprus	10
Egypt	18
Estonia	18
Georgia	10
Iceland	4
Iran	22
Ireland	7
Korea	103
Lithuania	16
Mexico	40
Montenegro	1
Morocco	9
New Zealand	6
Pakistan	21
Peru	2
Saudi Arabia	3
Slovenia	25
South Africa	31
Thailand	6
T.F.Y.R.O.M.	1
Ukraine	26

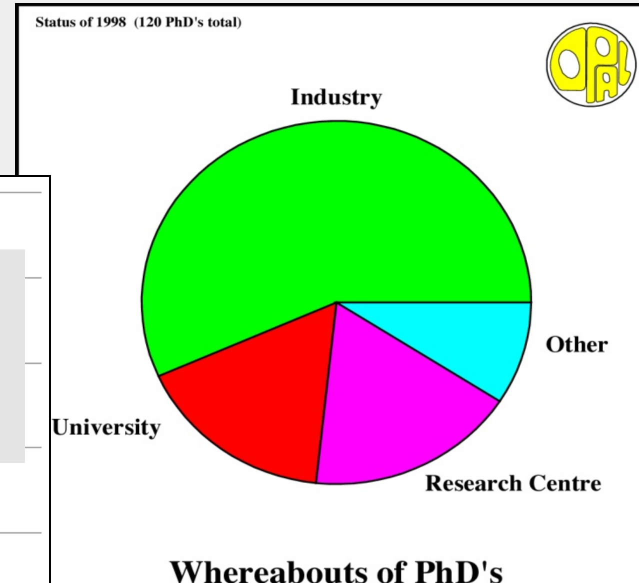
987

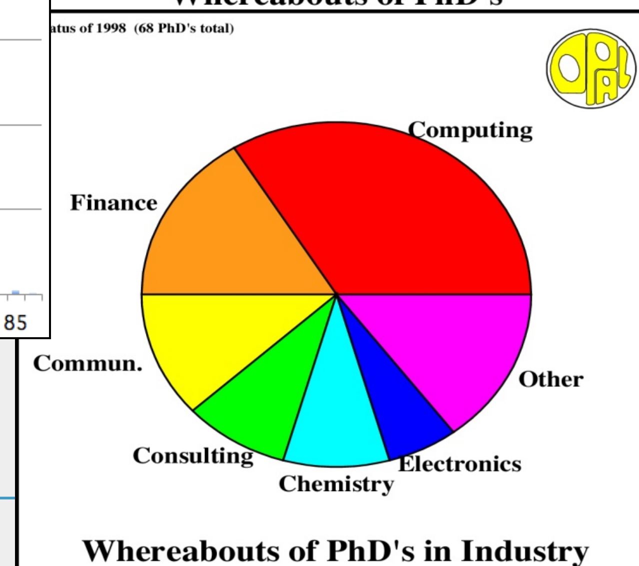
Age Distribution of Scientists
- and where they go afterwards

Survey in March 2009

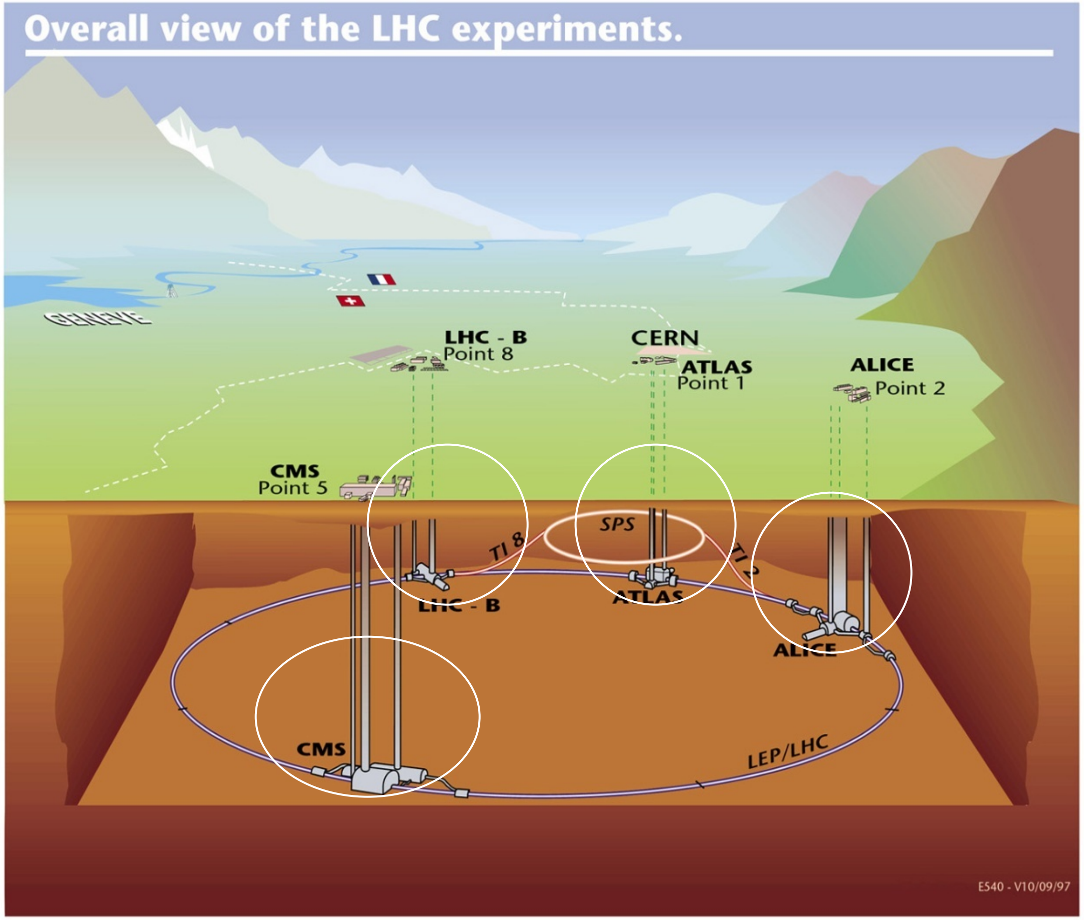


They do not all stay: where do they go?





The LHC tunnel is at 100 m underground

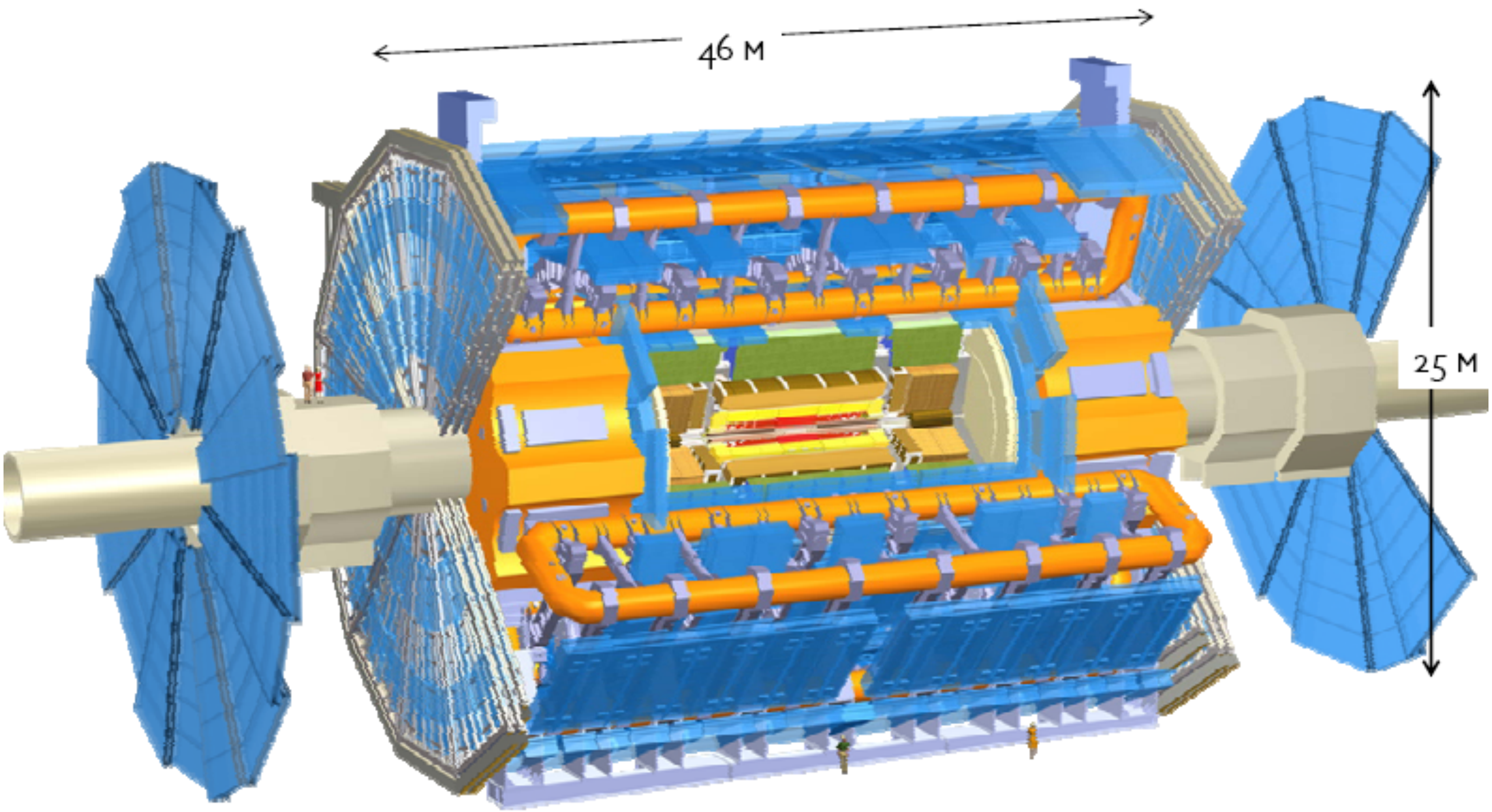


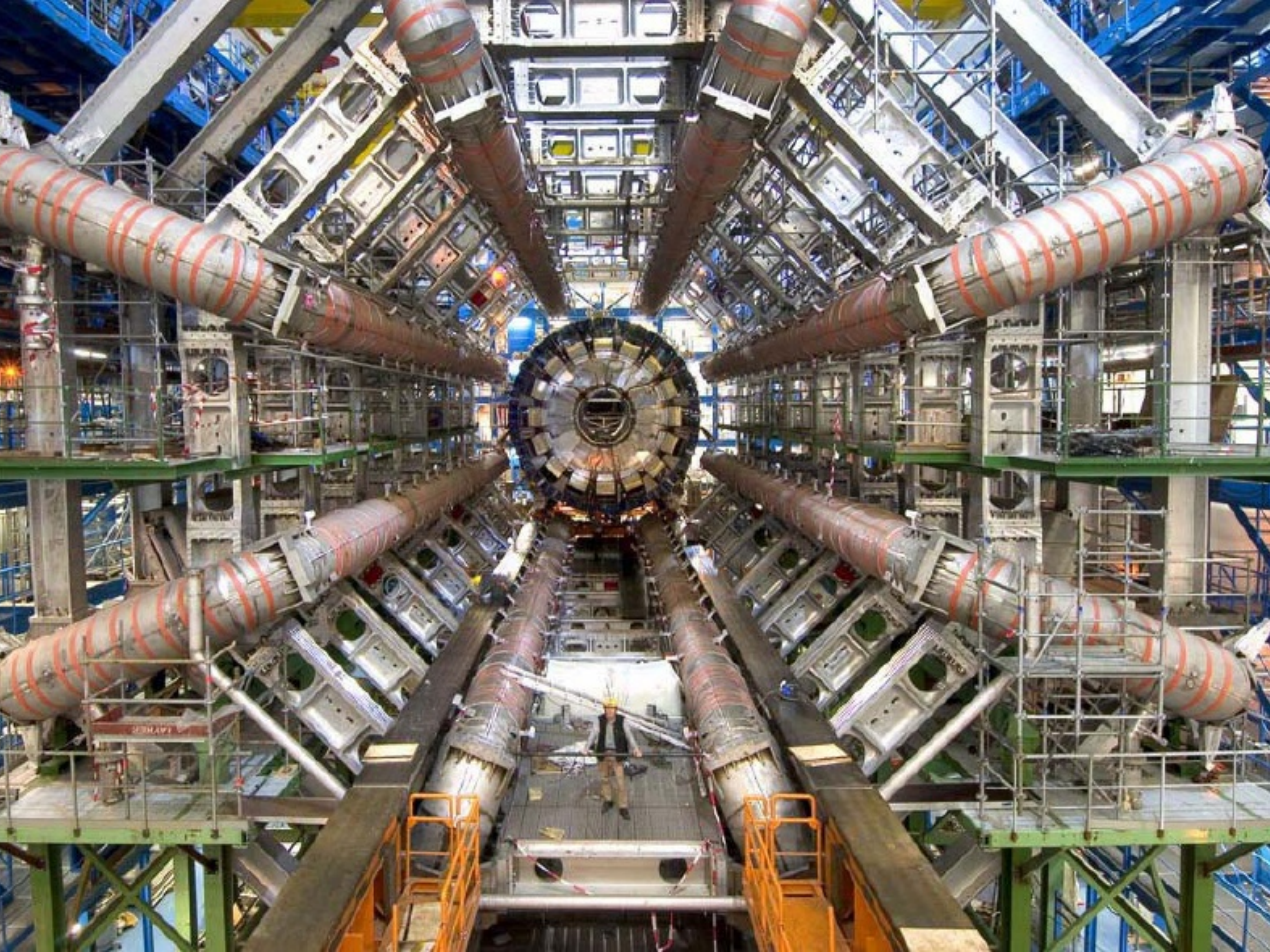
- 4 gigantic caverns host 4 huge detectors
- center of mass energy of 14 TeV, never reached before
- beam intensity orders of magnitude higher than before
- almost 40.000 ton of material at 1.9 K, a temperature lower than the cosmic background

ATLAS → atlas.ch

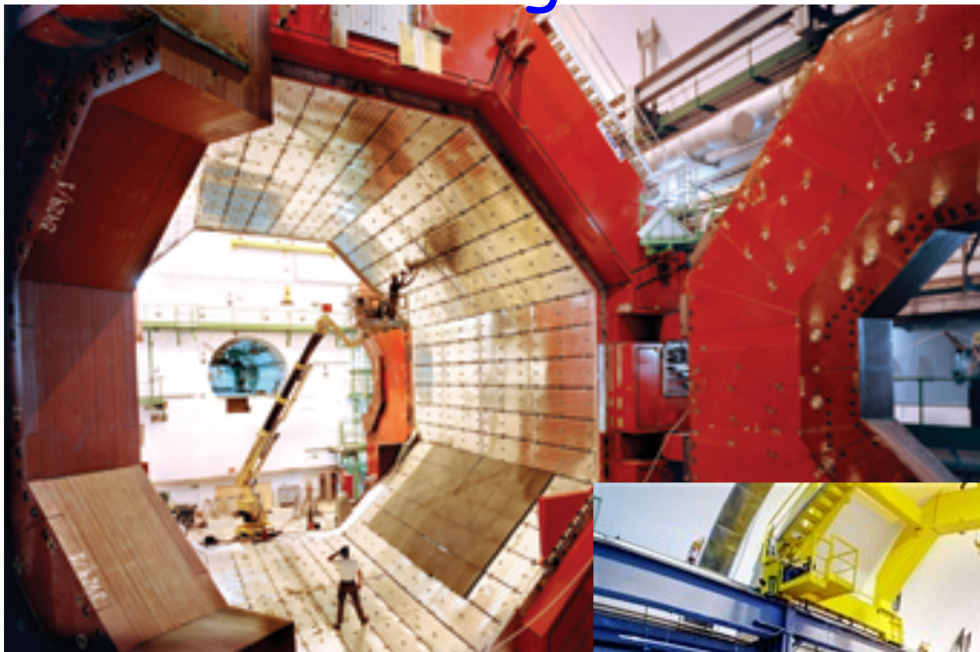
7000 t – 100,000,000 canali di elettronica - 2100 scienziati, 37 nazioni, 167 istituti

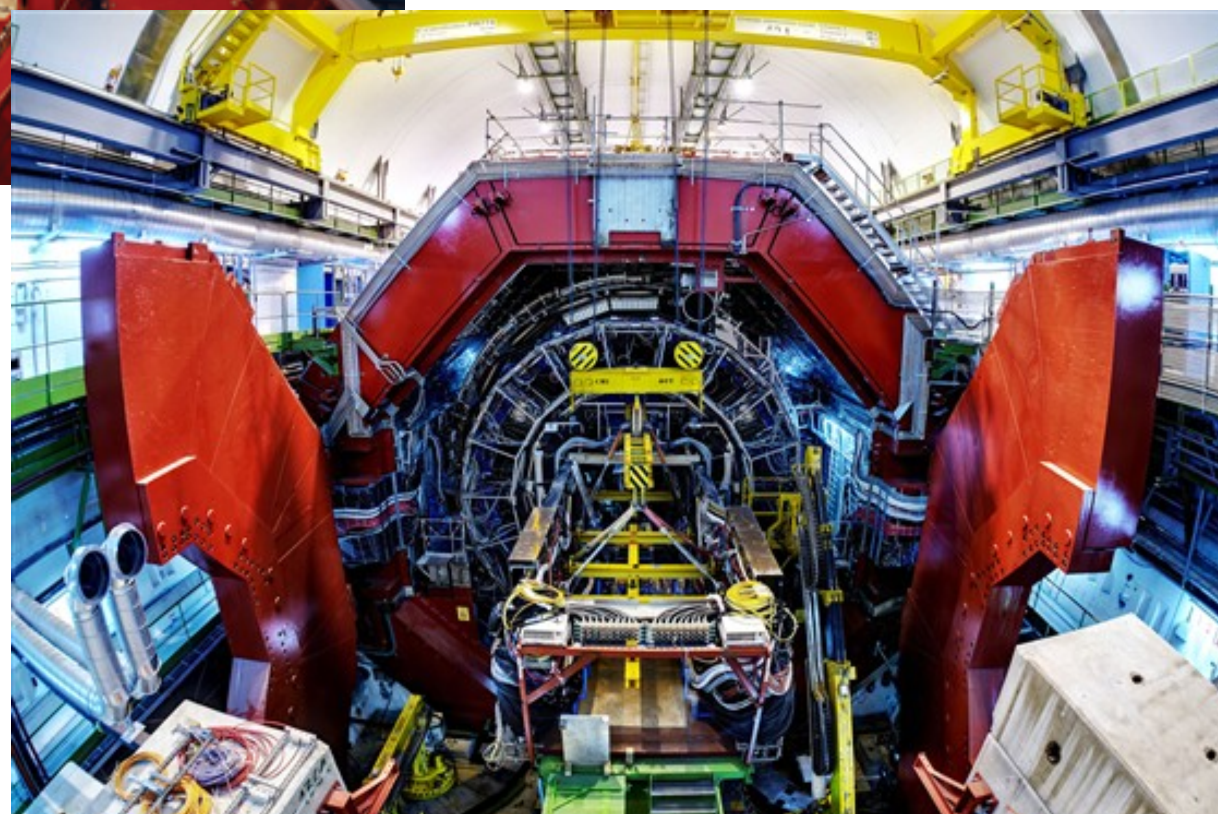
Costo 400 M€





ALICE magnet



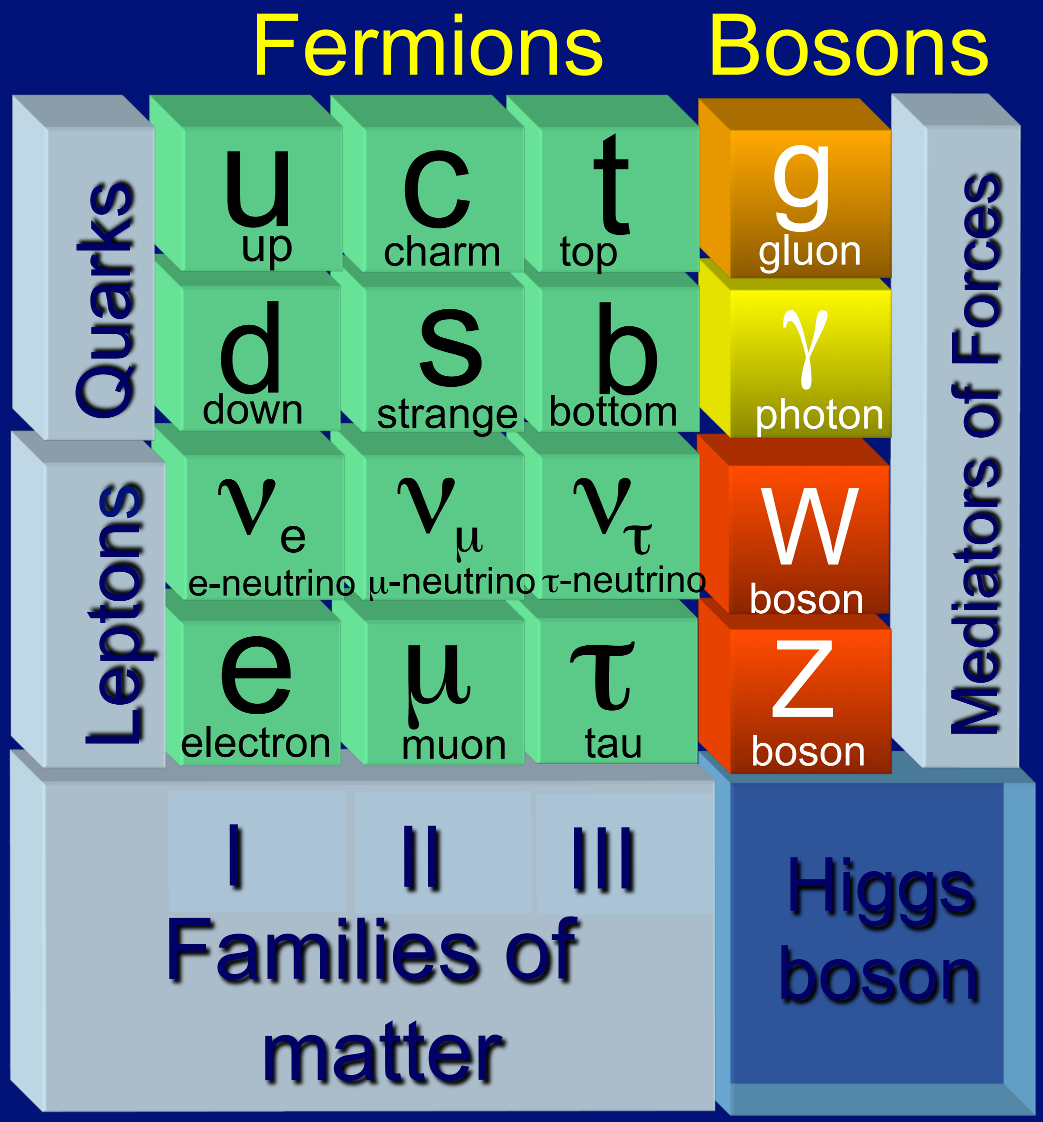


ALICE

The first step: the briks of the Universe…

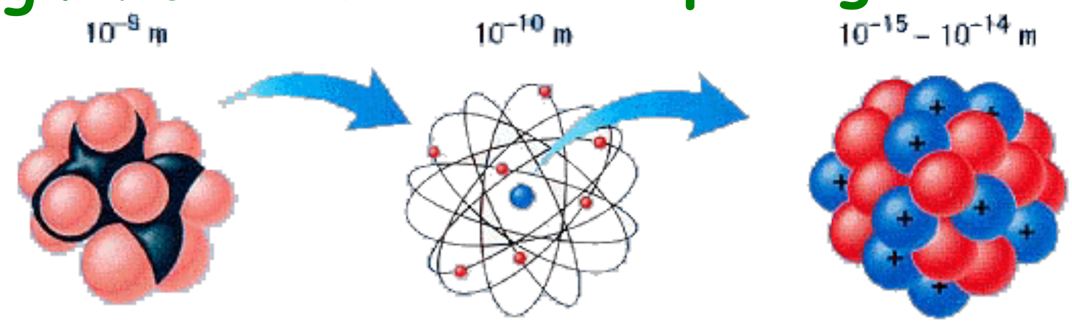
The Standard Model

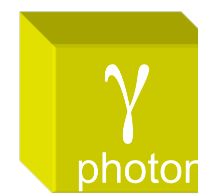
The Standard Model

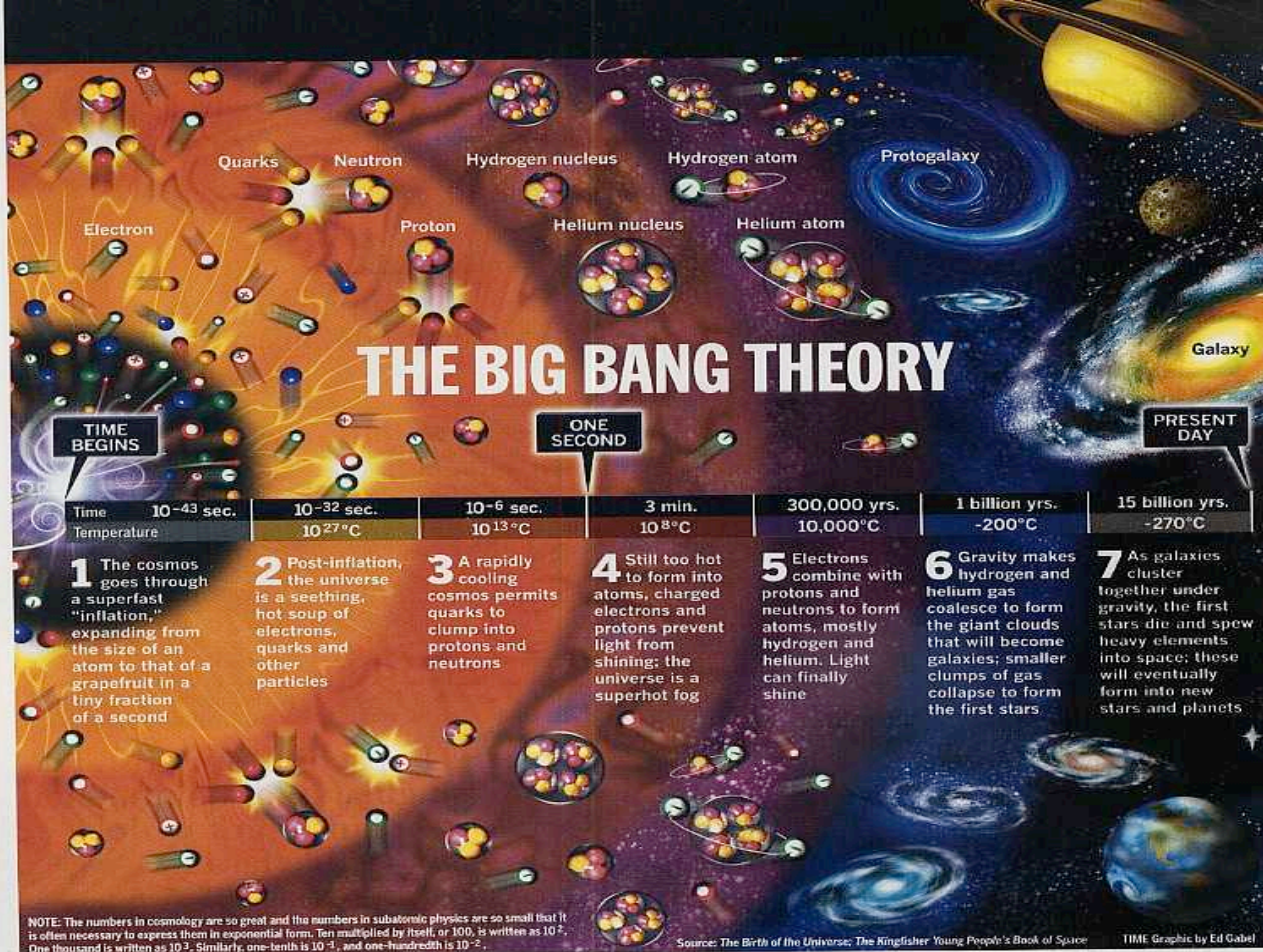


The fundamental interactions

Interaction	Strength	Effect
Gravitational	1	Keeps you on the ground
Weak	10^{29}	Decay: $n \rightarrow p + e^{-} + n$
Electromagnetic	10^{40}	Keeps together the atoms
Strong	10^{43}	Keeps together the nuclei

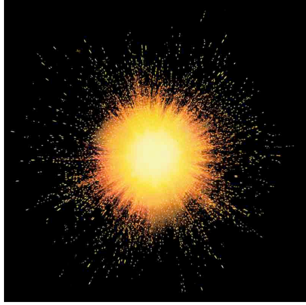






THE BIG BANG THEORY
Quarks
Neutron
Hydrogen nucleus
Hydrogen atom
Protogalaxy
Electron
Proton
Helium nucleus
Helium atom
Galaxy
TIME BEGINS
ONE SECOND
PRESENT DAY
Time
Temperature
10-43 sec.
10-32 sec.
10-6 sec.
3 min.
300,000 yrs.
1 billion yrs.
15 billion yrs.
1027°C
1013°C
108°C
10,000°C
-200°C
-270°C
1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second
2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles
3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons
4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog
5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine
6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars
7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets
NOTE: The numbers in cosmology are so great and the numbers in subatomic physics are so small that it is often necessary to express them in exponential form. Ten multiplied by itself, or 100, is written as 102. One thousand is written as 103. Similarly, one-tenth is 10-1, and one-hundredth is 10-2.
Source: The Birth of the Universe; The Kingfisher Young People's Book of Space
TIME Graphic by Ed Gabel

A Mini-Bang in the lab



- We need a small system so that it can be accelerated to ultrarelativistic speed (99.9% c)
- That system (i.e. a chunk of matter and not just a single particle) must follow simple rules of thermodynamics and form a new state of matter in a particular phase
- We can use heavy ions (e.g. Pb). They are tiny ($\sim 10^{-14}$ m) but have a finite volume that can be exposed to pressure and temperature

We will try to force matter, through a phase transition, to a new state of matter called "Quark Gluon Plasma"

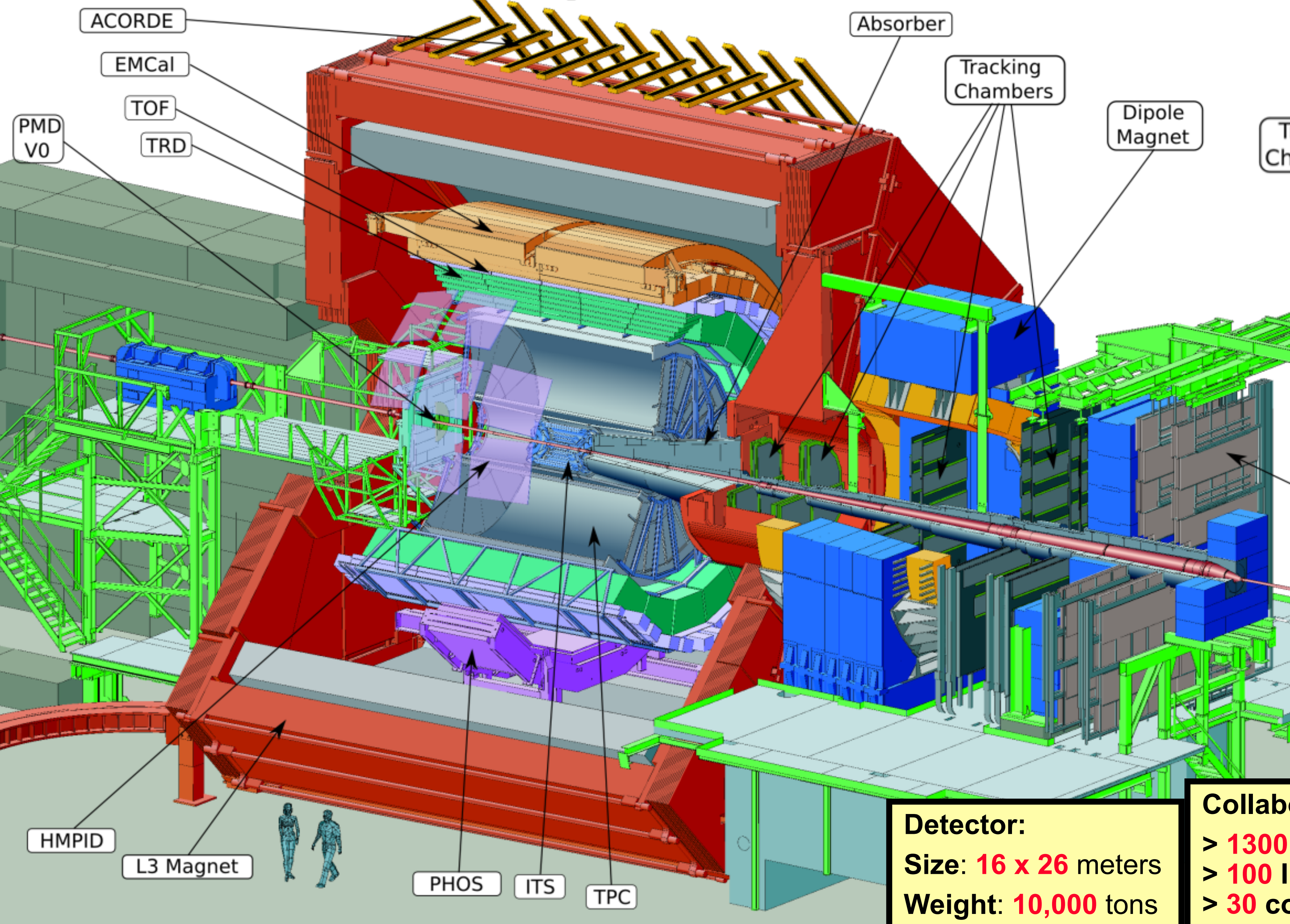
We need Heavy Ions

2 nuclei colliding at very high energy

A Large Ion Collider Experiment

ALICE

European Organisation for Nuclear Research



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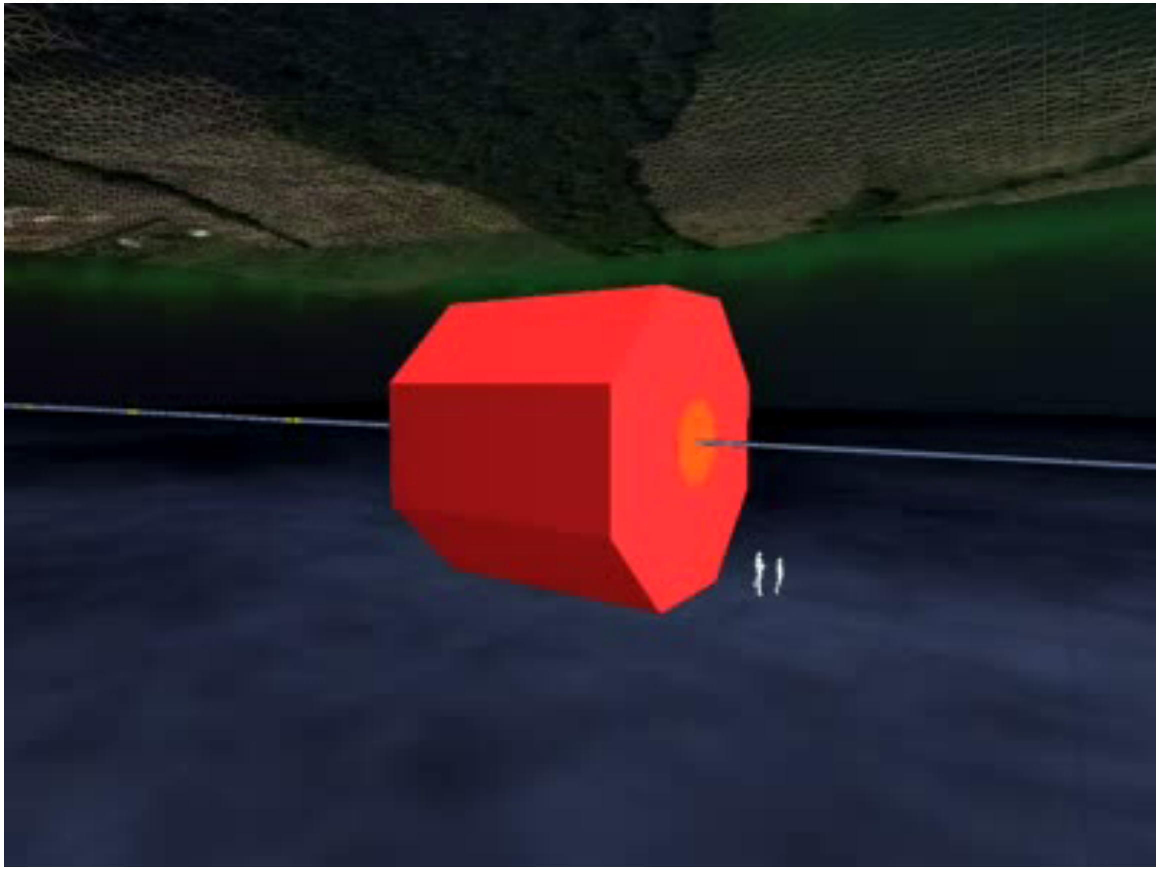
A simulated collision in Alice

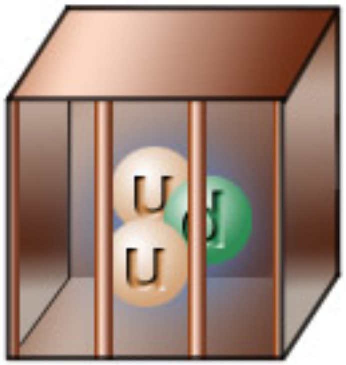


Up to 10^{-37}-10^{-5} s from the Big Bang the Universe was formed by a "soup" of quarks and gluons … the Quark Gluon Plasma (QGP)

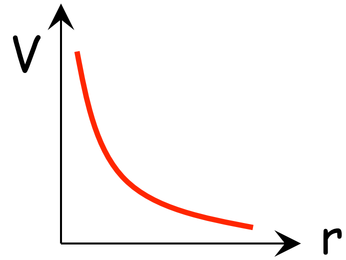
- Why to study the QGP?
- Which are the main features of the QGP?
- Is it possible to have such a system in laboratory?

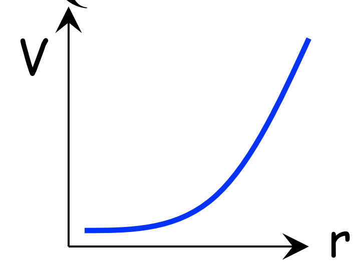
-T_{QGP}=2000 billions K
-T_{SUN}=15 millions K

Asimptotic freedom → Confinement



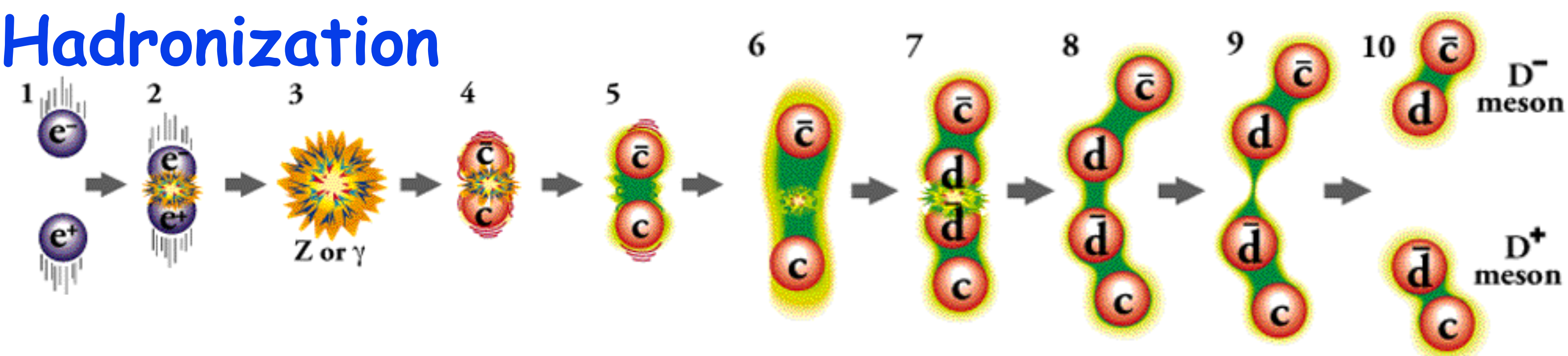
$$V_{Coulomb} \propto \frac{q_1 q_2}{r} \Rightarrow V_{QCD} \propto e^{k\cdot r}$$



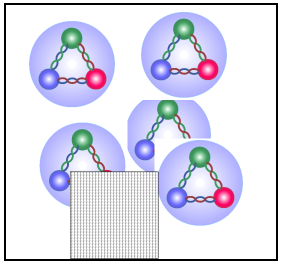


Separating interacting quark, a tension (energy) able to create new particles is formed (1000 MeV / fm)

Hadronization

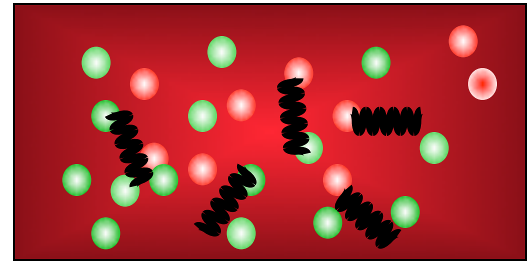


We need to create a system with hugh energy density (particles at infinitesimal distance) in order to have a negligible strong interaction



Hadrons

ENERGY



Quark Gluon Plasma

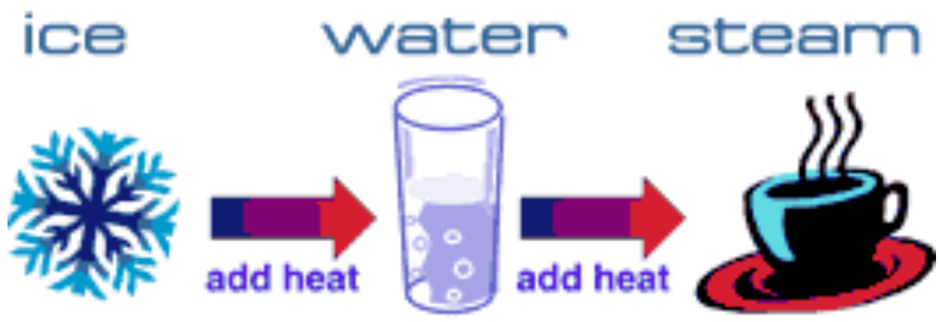
Nobel Prize 2005

D. Gross
H.D. Politzer
F. Wilczek

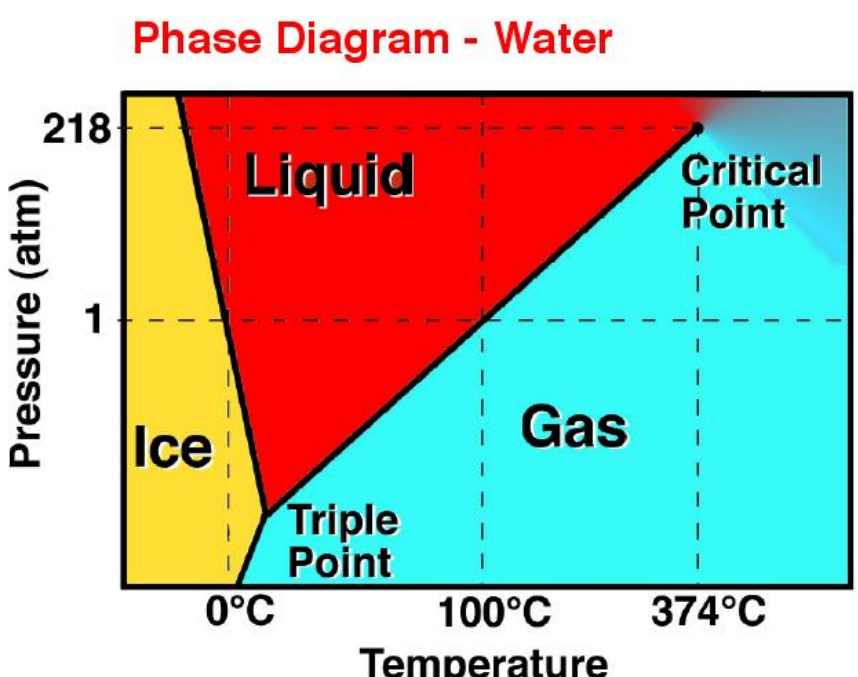
QCD Asymptotic Freedom (1973)

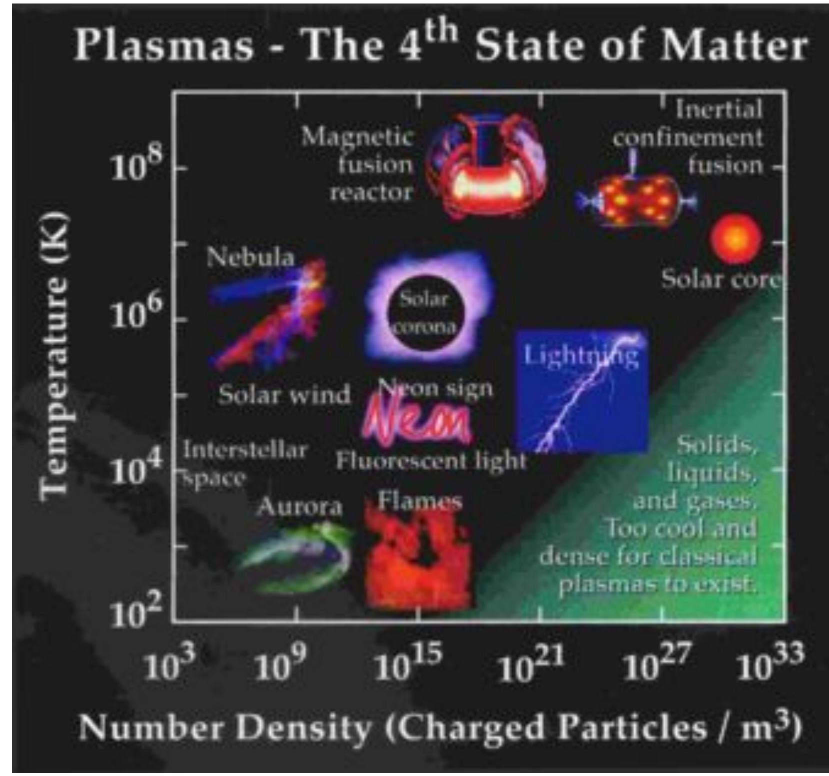
"Before [QCD] we could not go back further than 200,000 years after the Big Bang. Today…since QCD simplifies at high energy, we can extrapolate to very early times when nucleons melted…to form a quark-gluon plasma."
David Gross, Nobel Lecture (RMP 05)

Phases of the "normal" matter



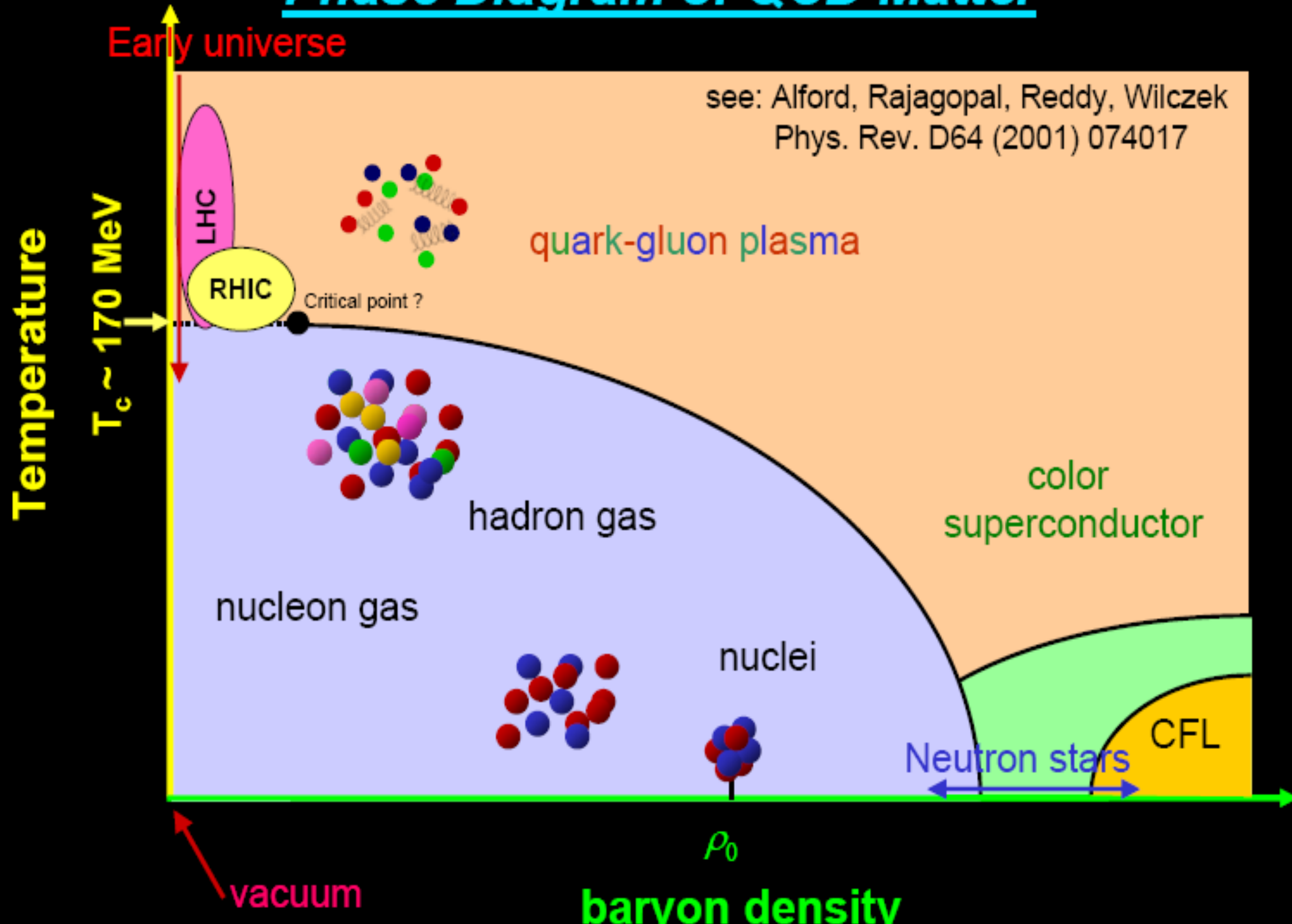
solid liquid gaseous



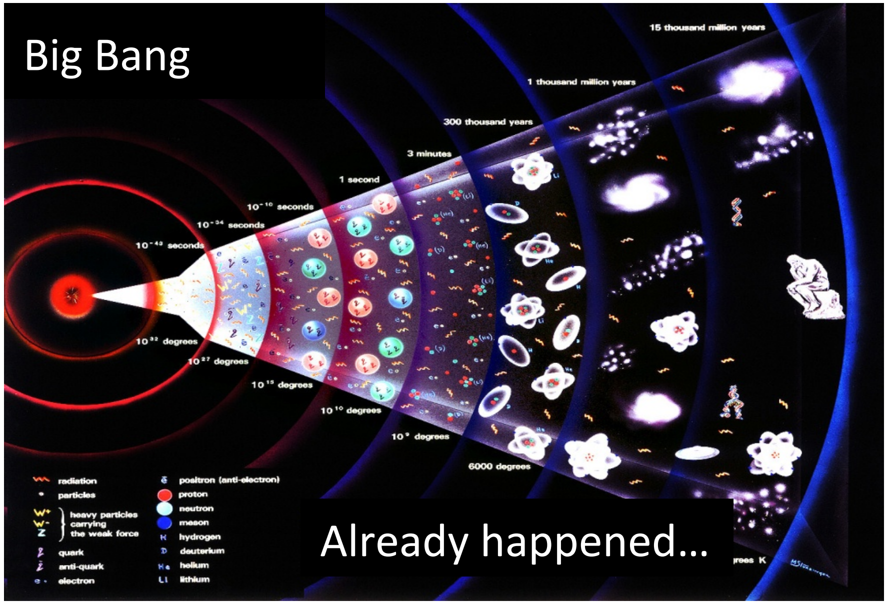


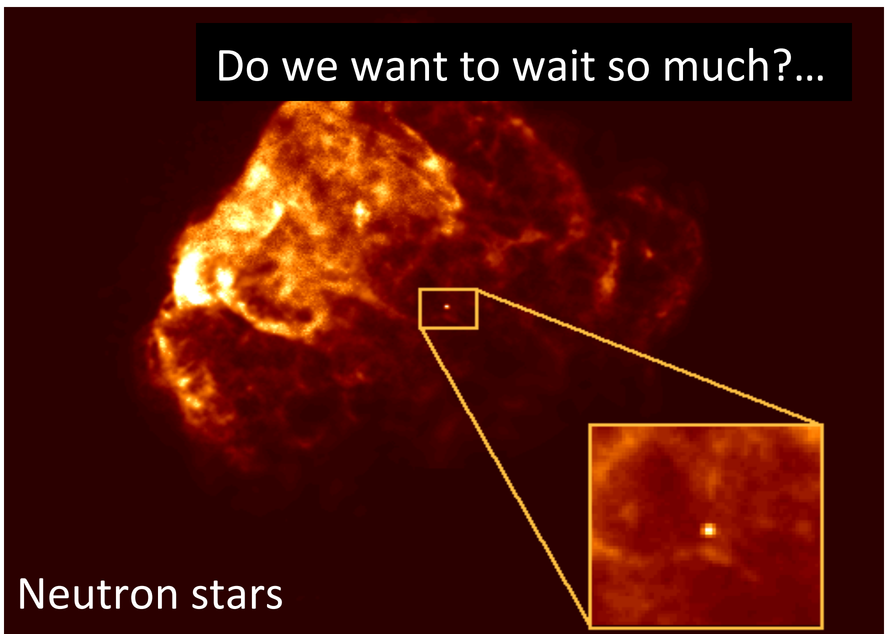
Classic Plasma

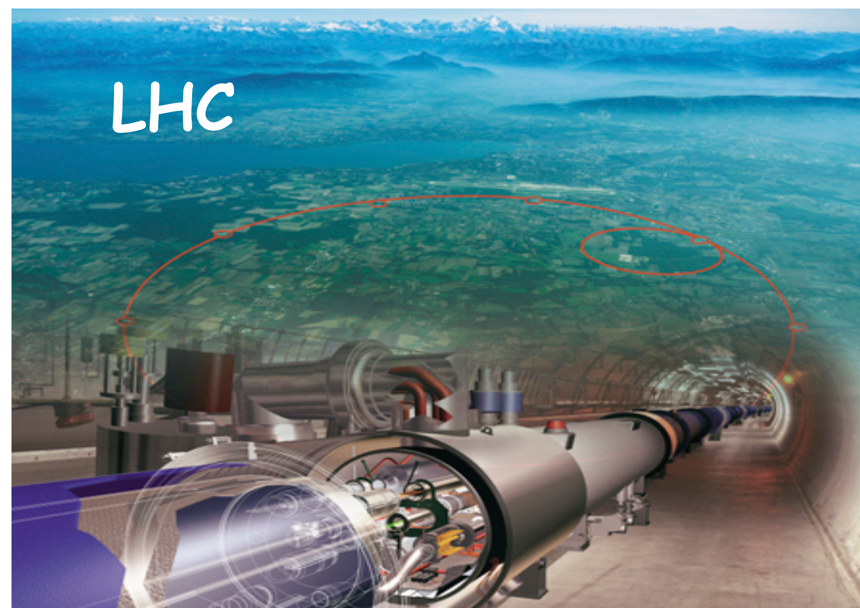
Phase Diagram of QCD Matter



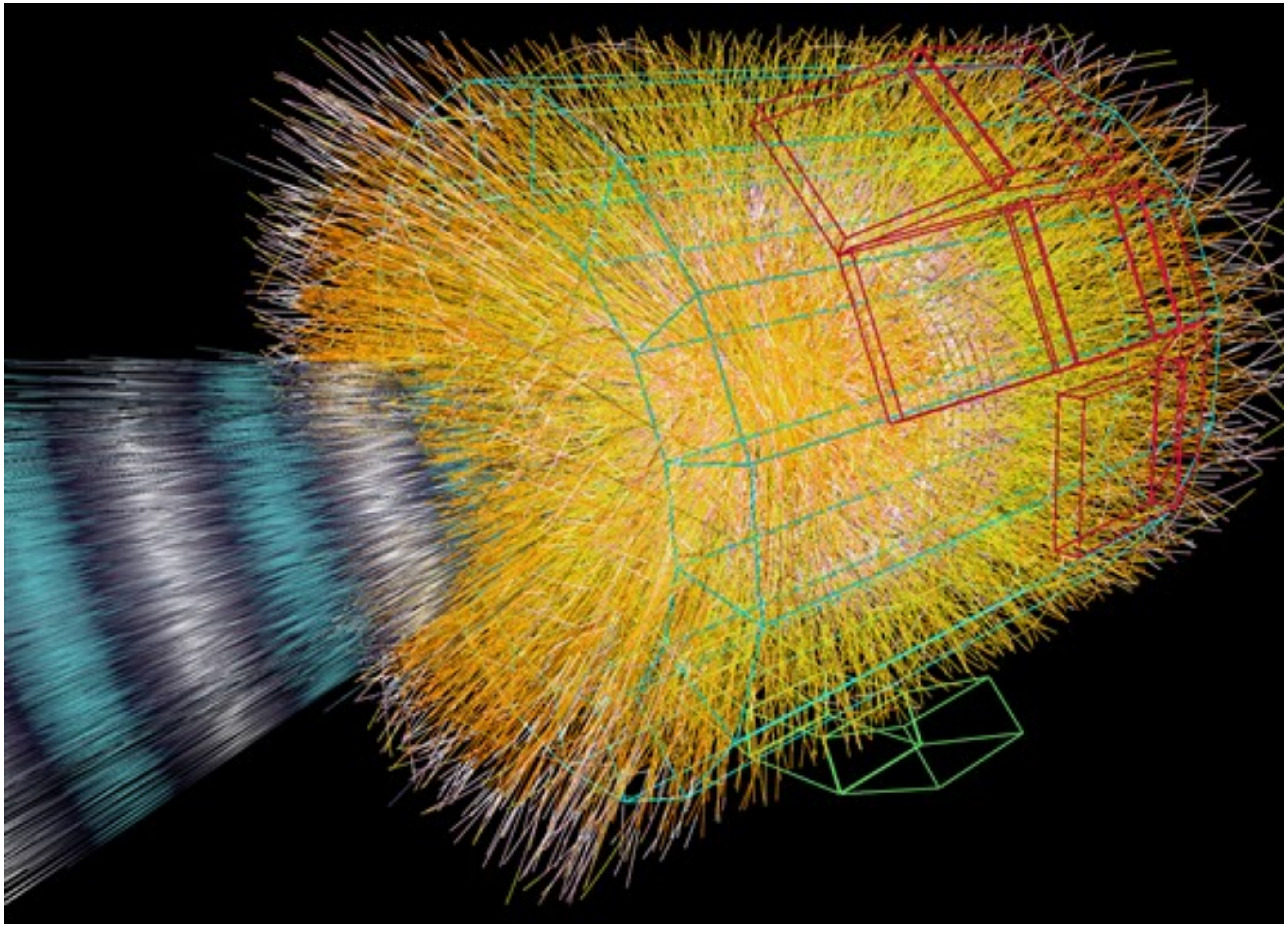
Where can we produce the QGP?







Pb+Pb event in Alice



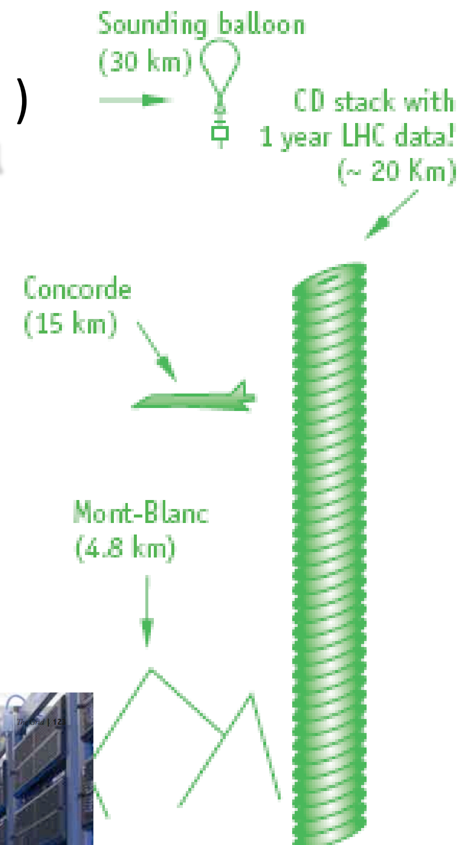
Thousands of particles produced per collision (25 ns)

Data Acquisition and Analysis

Experimental data at the LHC

- The quantity of produced data is enormous!

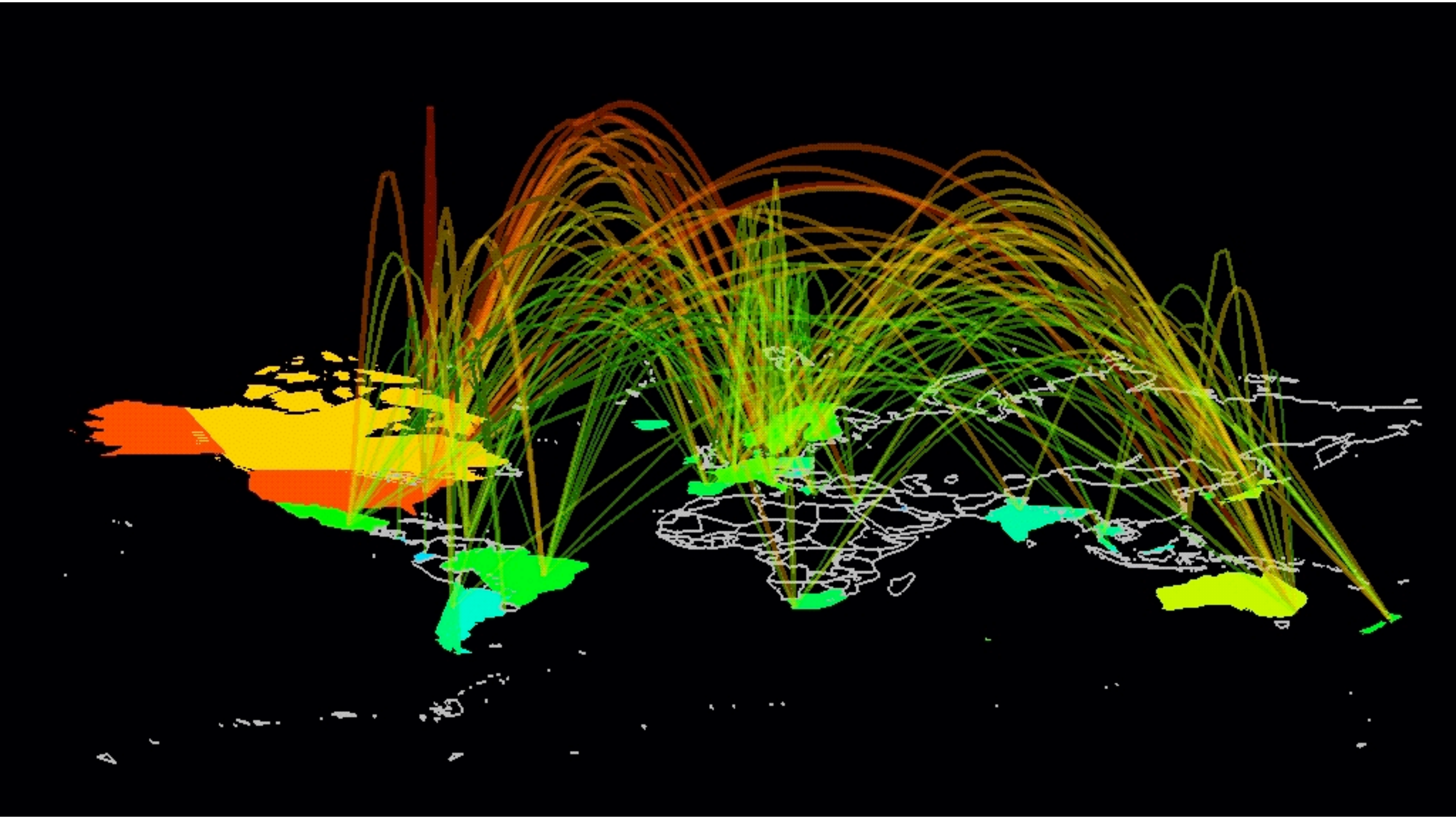
~1.3 GB/s → 6 times the Britannic Encyclopedia



- If we had to store those data on CD we should need a stack of disks 20 km tall … each year!

- New computing solutions developed: GRID

GRID architecture



Can a Black Hole be produced at the LHC?

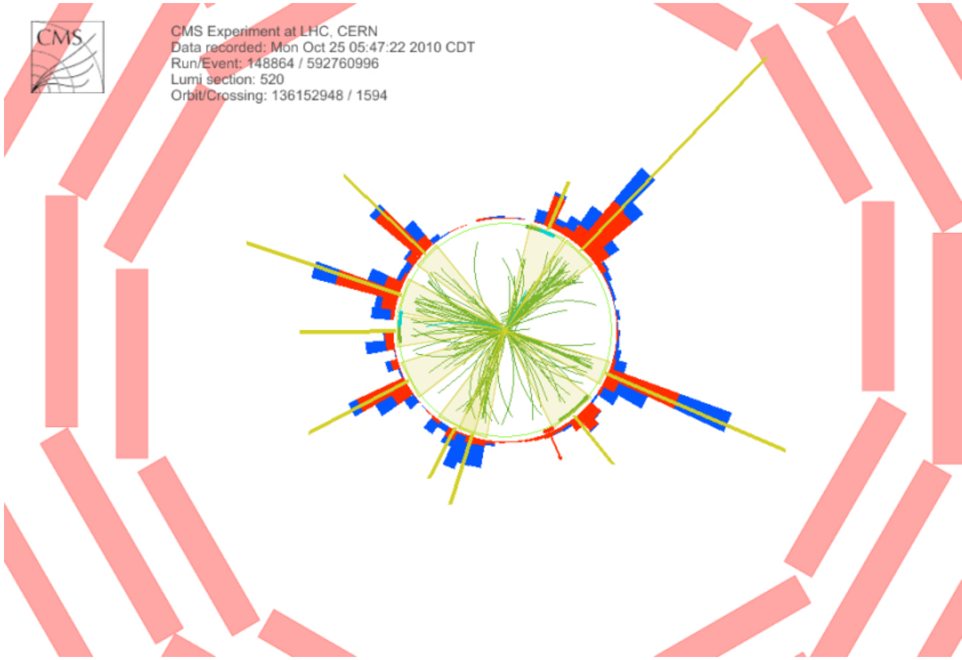
"It's black, and it looks like a hole. I'd say it's a Black Hole."

Black Holes evolution and decay

- Mini black holes produced at LHC would be light and tiny compared to cosmic black holes (~TeV versus ~3 Solar masses)
- This means they would be extremely hot (T~100 GeV) and evaporate almost instantaneously, mainly via Hawking radiation

- → cosmic BH 10^{19} GeV → LHC energy ~10^{4} GeV

- Typical decay signature:
  ~6 ptc for each decay emitted spherically
  - 75% quarks and gluons
  - 10% charged leptons
  - 5% neutrinos
  - 5% of photons or W/Z boson
  - new ptc around 100 GeV



BH event simulated by CMS

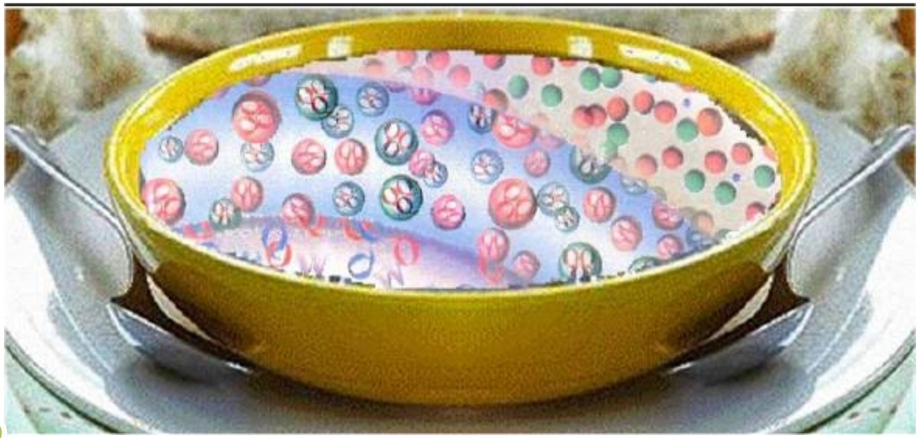
A "soup" reach of information

Space-time evolution of the birth of a hadron

Properties of QCD at high temperature: degrees of freedom, viscosity, conductivity, …

Elliptic Flow

Restauration of chiral symmetry



Freezout

Puzzle barionico

Plasma and color caos instability

Phase transition in cosmological theories of the primordial Universe

Equation state of QCD

Partonic energy loss

Chemical composition

Global observables summary

The Early Universe behaved as a perfect fluid

Something less interesting … at least for you

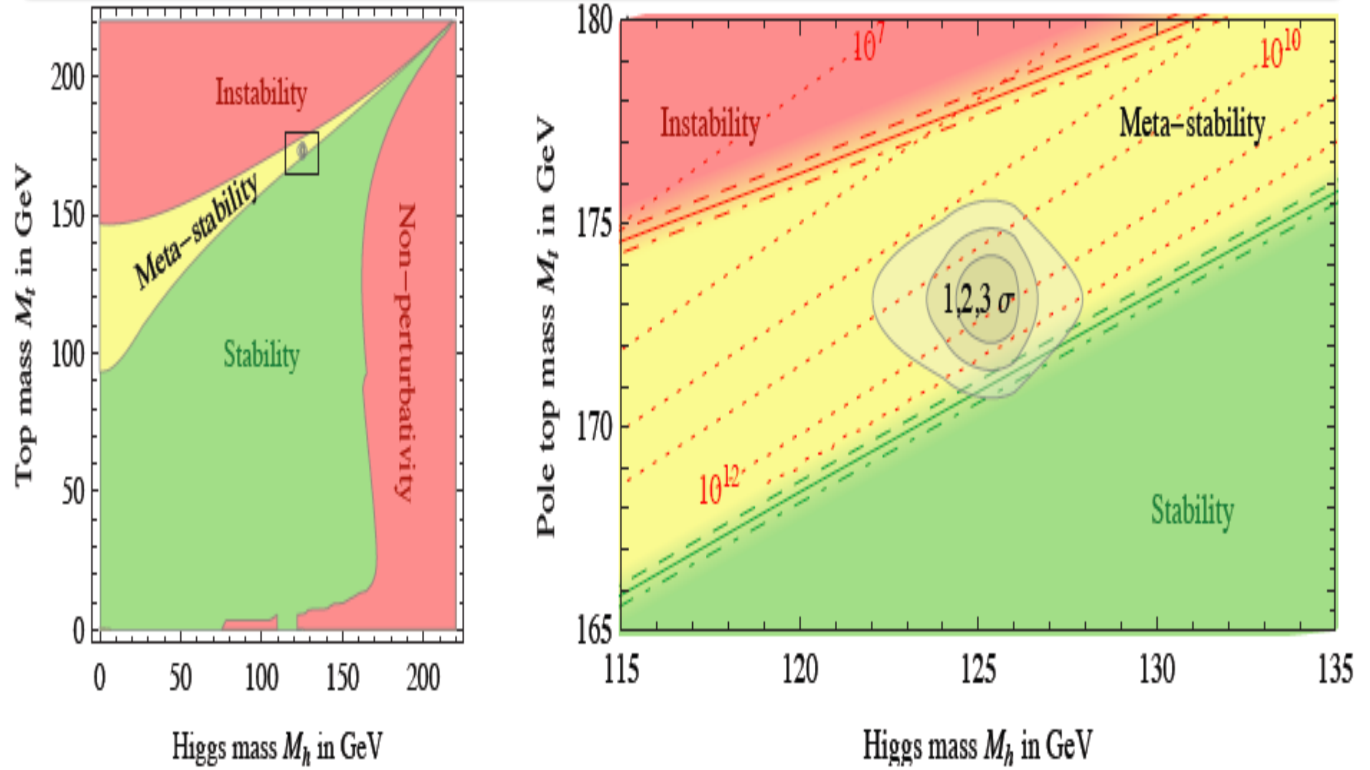
- Energy density > 50 GeV/fm^3
- Freeze-out volume ~300 fm^3
- Time scale until decoupling 10 fm/c
- Elliptic flow as expected from hydro-dynamical calculations
- Initial state saturation effects smaller than expected

Conclusions

Alice and the LHC are operating wonderfully unveiling the first secrets of the Early Universe

A new and unique era for the exploration of the matter just started. The connections with other branches of physics are incredibly high and intriguing

"Dangerous" life in a Metastable Universe



I'm still confused …

… but at high level !

E.Fermi, Chicago 1951